OPTIMAL DESIGN OF INTER-PLANT WATER NETWORK WITH CENTRALIZED REGENERATION SYSTEM

HAZLINDA BINTI SAPEE

Thesis submitted in fulfilment of the requirement
for the award of the degree of
Bachelor of Chemical Engineering in Chemical Engineering

Faculty of Chemical Engineering and Natural Resources
UNIVERSITI MALAYSIA PAHANG

JULY 2012

SUPERVISOR'S DECLARATION

I/We* hereby declare that I/We* have checked this thesis/project* and in my/our opinion, this thesis/project* is adequate in terms of scope and quality for the award of degree of Bachelor of Chemical Engineering in Chemical Engineering

Signature
Name of Supervisor: ZAINATUL BAHIYAH BINTI HANDANI
Position:
Date:

Signature
*Name of Co-supervisor:
Position:
Date:

*Delete if unnecessary.

ABSTRACT

Water is a basic raw material in an industry. Without it, the production cannot run or will be hindered. But, nowadays we are lacking reliable sources of water. In the future, two thirds of the world population will face water crisis or stress by the year 2025. In 2025, industrial growth will rapidly speed up, hence the sources of water will be limited. The negative effect of lack of sources of water make the cost of the water will be increasing. Hence, a new model has been developing based on water network superstructure to simultaneously generate the maximum water recovery targets and design minimum water network. Nowadays, water system integration becomes the research focus, because the technology is effective for saving fresh water and reducing wastewater generation. The purpose of this study is to develop a systematic technique for designing the minimum water network for inter-plant with centralized regeneration system. This problem is formulated as mixed integer nonlinear programming (MINLP) based on water network superstructure and is implemented in Generalized Algebraic Modeling System (GAMS) in order to obtain simultaneous minimum water targets and design of water networks. The effectiveness of the proposed model is illustrated by using an industrial case study. A significant reduction of fresh water consumption and waste water generation has been achieved, illustrating the effectiveness of the proposed approach. The result show the potential maximum freshwater and wastewater reduction are 53.63% and 61.65% respectively.

ABSTRAK

Air merupakan bahan asas dalam industry. Tanpa air, pengeluaran tidak boleh beroperasi atau operasi akan terhalang. Tetapi, pada masa sekarang kita kekurangan sumber air. Pada masa akan datang, dua pertiga daripada penduduk dunia akan menghadapi krisis air atau tekanan menjelang 2025. Pada tahun 2025, pertumbuhan perindustrian yang amat pesat, maka sumber air akan menjadi semakin terhad. Kesan negative kerana sumber air yang terhad akan menjadikan kos air akan meningkat. Oleh itu, sebuah model telah dibangunkan berdasarkan superskruktur rangkaian air bagi menghasilkan sasaran pemulihan air yang maksimum serta mereka bentuk rangkaian air yang minimum. Pada hari ini, integrasi sistem air menjadi tumpuan penyelidikan kerana teknologi ini berkesan untuk menyimpan air bersih dan mengurangkan penghasilan air sisa buangan. Tujuan kajian ini adalah untuk membangunkan teknik sistematik untuk mereka bentuk rangkaian air minimum bagi antara loji-dengan sistem penjanaan semula berpusat. Masalah ini dirumuskan sebagai pengaturcaraan tidak linear (MINLP) berdasarkan superstruktur rangkaian air and dilaksanakan dalam Generalized Algebraic Modeling System (GAMS) bagi mendapatkan sasaran air yang minimum dan reka bentuk rangkaian air. Keberkesanan model yang dicadangkan adalah digambarkan dengan menggunakan kajian kes industri. Pengurangan yang ketara penggunaan air bersih dan penghasilan air sisa buangan dapat dicapai, yang menggambarkan keberkesanan pendekatan yang dicadangkan. Keputusan ini menunjukkan potensi maksimum pengurangan air bersih dan air sisa buangan adalah sebanyak 53.63% dan 61.54%.

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LIST OF SYMBOLS

i	Set of process sources
j	Set of process demand
k	Set of network
c_{mix}	Concentration of contaminant of the water mixture in utility hub
C_D	Maximum concentration of contaminant in demand j
C_S	Maximum concentration of contaminant in source i
C_W	Concentration of contaminant in freshwater
F	Reuse/recycle flow rate from source i to demand j
F_{exp}	Export flow rate from source i to demand j
F_{imp}	Import flow rate to demand j for indirect integration
F_W	Fresh water flow rate required by demand j
W	Unused portion of water source i
f_{cp}	Total export cross-plant flow rate from water network k to utility hub for indirect integration
g_{cp}	Total import cross-plant flow rate from utility hub to water network k for indirect integration
m_{reg}	Total contaminant mass load removed through wastewater regeneration
x_{ind}	Binary variable for export cross-plant pipelines for indirect integration
y_{ind}	Binary variable for import cross-plant pipelines for indirect integration
LB_{cp}	Lower bound of cross-plant flow rate for both direct and indirect integration
UB_{cp}	Upper bound of cross-plant flow rate for both direct and indirect integration

RR	Fixed removal ratio
D	Flow rate of water source *i*
S	Flow rate of water demand *j*
N	Total number of cross pipelines
F	Water flow rate entering and leaving
m	Mass load of the contaminant
Cin	Inlet concentrations of contaminant the water stream
Cout	Outlet concentrations of contaminant the water stream

LIST OF ABBREVIATIONS

GAMS	General Algebraic Modelling System
LP	Linear Program
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MTB	Mass Transfer Based
NMTB	Non Mass Transfer Based
TDS	Total Dissolve Solid
WCA	Water Cascade Analysis

CHAPTER 1

INTRODUCTION

1.1 GLOBAL WATER OUTLOOK

Most of the Earth’s surface is covered in water. It covers about two-thirds of the Earth's surface which is about 70.9% but only 2.5% are fresh water. Fresh water can be defined as water with less than 0.5 parts per thousand of dissolved salts. It comes from the rain and snow that falls into a river and lakes. It also can be found in the groundwater, cave water, springs, floodplains, and wetlands. For the seawater, it contains about more than 50 parts per thousand of dissolved water make it not suitable for the life (Water: our rivers, lakes & wetlands). Figure 1.1 depicts the percentages of the sources of fresh water. Figure 1.1 show that the main sources of the fresh water is ice and snow which is about 68.7%. The second source of water is fresh groundwater (30.1%) followed by permafrost (0.86%), lakes (0.26%), soil moisture (0.05%), wetlands (0.03%) and the last is rivers which is about (0.006%).

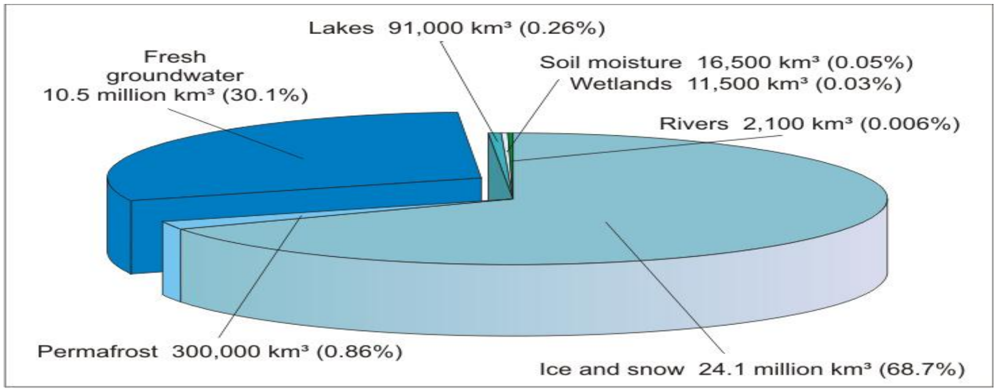

Figure 1.1: The world's fresh water resources

Water is the main part for the agriculture, industry and domestic use. Without it, for example, the plant cannot survive or will be hindered. For the industry, the operation of plant also cannot operate because majority of the plant use water. Water is mainly use in the agriculture follow by domestic, industrial and the last for reservoirs. The global water use is shown in Figure 1.2. From the figure, it is clearly shown that the highest water consumption is come from agriculture sector where the trend of water usage is increase from 1900 and it is predicted to be increased up to 3200 km2 in 2025. The second main usage of water is come from domestic sector, followed by industrial and reservoirs use.

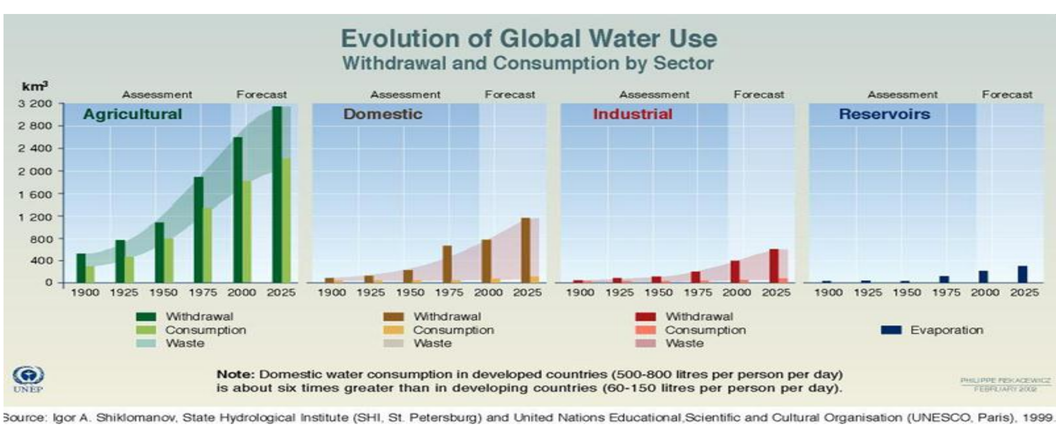

Figure 1.2: Global water uses

Figure 1.3 depicts the percentages of the water use in the world. It is clearly shows that agriculture is major sector that use water which is about 67%. The second sector of the water use is households (9%), followed by water supply (8%), electricity and gas (7%), manufacturing (2%), other (3%) and the last is mining which is about 2%.

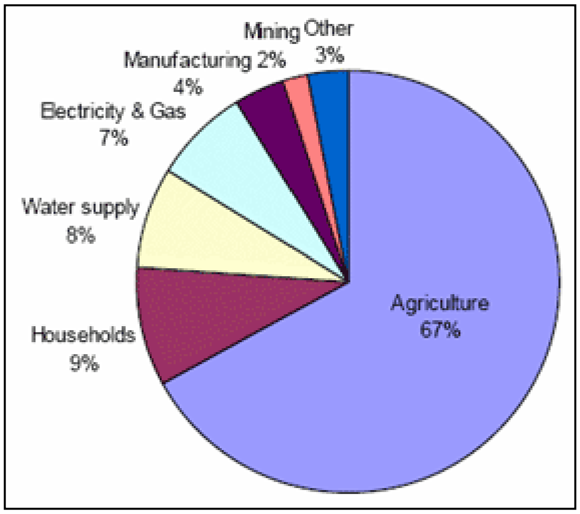

Figure 1.3: Water use in the world (2005)

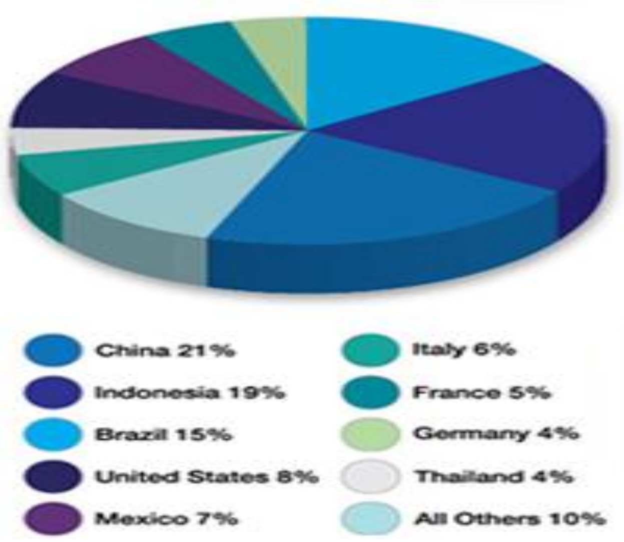

Figure 1.4: Global water uses (Pure water)

From the figure 1.4, water is mainly use in the China which is about 21% followed by Indonesia which is about 19 %. The main sector in the China is agriculture. That why this country uses a lot of fresh water in order to generate their agriculture sector.

1.2 PROBLEM STATEMENT

For the future, two third of the world population will face the water crisis or stress by year 2025. At this period, the sector of agriculture, industry and domestic will use more water. Besides that, the cost of freshwater also is increasing by year. In order to treatment the freshwater, more cost are needed because freshwater contain more contaminants. Hence, an effective measure is needed to reduce the usage of fresh water and wastewater in all sectors.

Over three decades, the main concern of wastewater is always focused on end-of-pipe treatment. Wastewater streams containing several contaminants (pH, total dissolve solid (TDS), hardness, heavy metal etc.) create an environmental pollution problem. It is important to note that end-of-pipe solutions have been employed as the only solution to meet the imposed discharge limits. However, due to water scarcity, fresh water minimization is being important agenda especially in industrial sector which also the minimization of water will also influence the wastewater minimization. Water system integration becomes the research focus, because this technology is effective for saving fresh water and reducing wastewater as it can assist organizations to maximize water saving. As a result, the current research on fresh water and wastewater minimization mainly focus on water integration.

1.3 RESEARCH OBJECTIVE

The main objective of this study is to develop the systematic technique for designing the minimum water network with centralized regeneration system.

1.4 SCOPE OF STUDY

The scope of study is focus on 3 topics. First, this study is to design an inter-plant water network. For the inter-plant, there are two types which is direct and indirect process. The centralized regeneration unit is added in indirect process. Second, this study is only focus on single contaminant which is heavy metal. Lastly, this study focuses on the method on how to solve the problem. Here, mathematical modeling method has been choosing to overcome this problem.

1.5 RATIONALE AND SIGNIFICANCE

After 2025, the industrial rapidly growth up, hence the source of water will be limited. The effect from this is cost of the freshwater also increases. Hence, to avoid this scenario happen, the wastewater from the plant can recycle and reuse in order minimize the usage of water. From water system integration technique, the cost of freshwater that needs to be paid by the plant or building owner and more money can be saved.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter recapitulates on the all article that have been read that relate to the research objectives. In here, there are three parts according to the objectives which contain mass transfer based (MTB) and non- mass transfer based (NMTB), inter plant water integration, and water system integration.

2.2 MASS TRANSFER BASED AND NONMASS TRANSFER BASED

Basically, there are two board categories which is mass transfer based (MTB) and non-mass transfer based (NMTB). For the MTB, it also knows as a fixed contaminant load problem (Handani et al., 2009). In this category, the operation is quality controlled (Polley and Polley, 2000) and water as the only mass separating agent. This principle assumes that the inlet and outlet flow rates are equal and is determined by

$$\Delta m = F\ (C_{out} - C_{in}) \tag{2.1}$$

where m is the mass load of the contaminant, F is the water flow rate entering and leaving, and C_{in} and C_{out} are the inlet and outlet concentrations of contaminant the water stream (Yongjian et al., 2007). The examples of this operation are washing, scrubbing and extraction. For example, during cleaning, water is fed into the vessel which is as a demand while wastewater is generated will act as a source as shown in Figure 2.1.

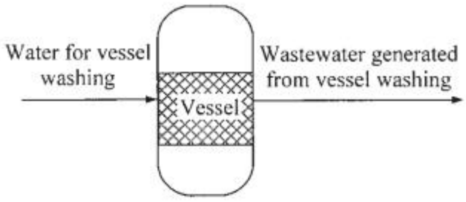

Figure 2.1: Mass transfer-based water-using operations in vessel washing

Other name of NMTB is the fixed flow rate operation which is quantity control (Polley and Polley, 2000) and it covers functions of water other than as a mass separating agent. In this category, the water flow rate is more important than the amount of contaminant accumulated. This unit has specified inlet and outlet flow rates, which may not necessarily be equal and therefore can account for water losses or generations. The outlet streams always leave at the maximum concentrations, while the inlet streams have maximum allowable concentrations (Prakash and Shenoy, 2005). The example of this operation is water is fed as a material or being withdrawn as a product or byproduct in chemical reaction as shown in Figure 2.2.

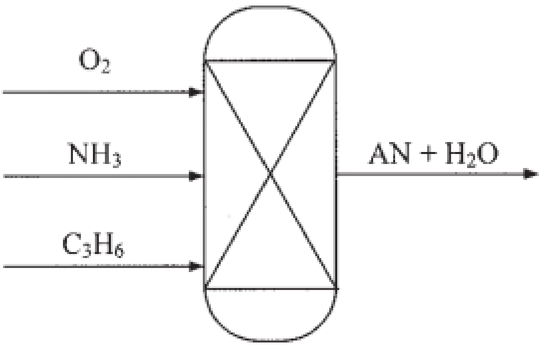

Figure 2.2: Non-mass transfer based water using operations in a reactor that produces water as a byproduct in acrylonitrile production

2.3 INTER – PLANT WATER INTEGRATION (IPWI)

The inter-plant water integration consist two or more intra-plant. Intra-plant is single water network, where water recovery is achieved by integrating water-using processes within the same network (Irene and Dominic, 2009). For inter- plant, it has two types which is direct and indirect integration. Rodera and Bagajewicz (1999) have introduced these two alternative schemes for interplant heat integration which is direct integration by using process streams and indirect integration using intermediate fluids.

2.3.1 Direct Integration

For the direct integration, water from different networks is integrated directly via cross-plant pipeline. Figure 2.3 describe the direct integration process. It shows that these schemes have 3 intra-plants at different location but connected directly using pipelines. Water from network A sent to network B and C or vise verse.

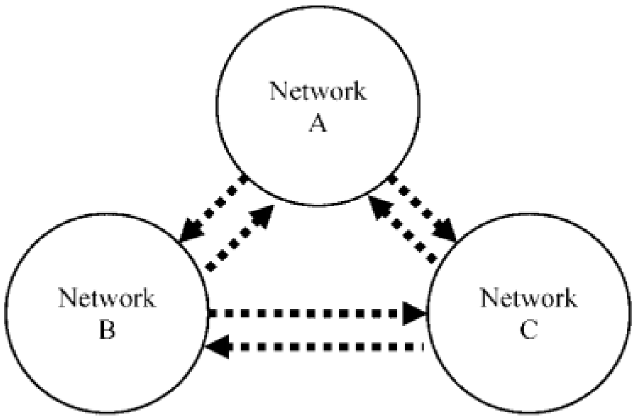

Figure 2.3: IPWI schemes (direct integration)

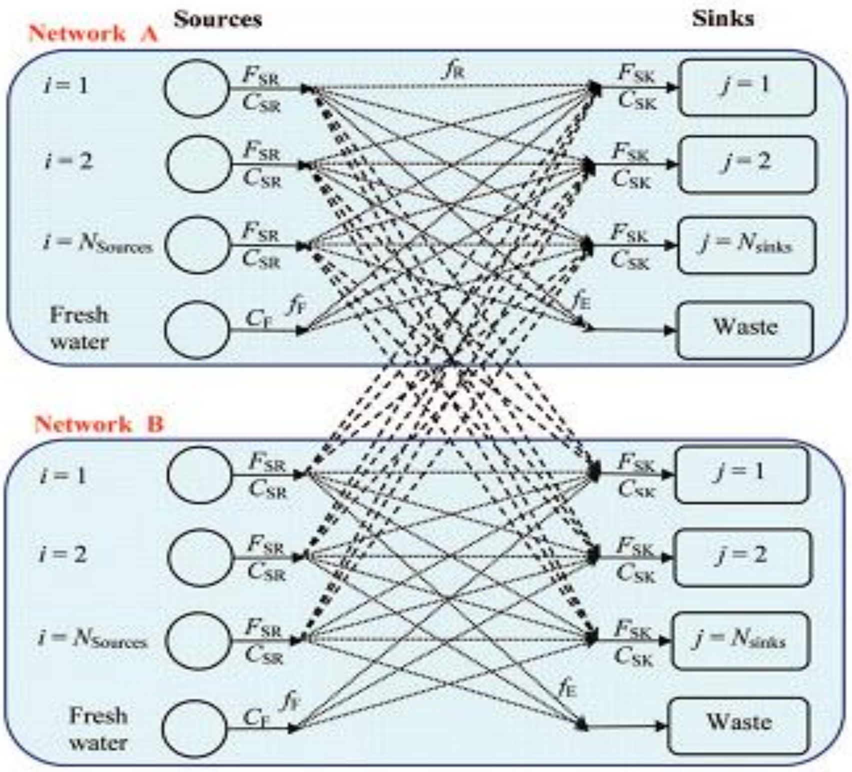

Figure 2.4: Superstructure for direct integration

Figure 2.4 depict the superstructure for direct integration. Apart from being reuse or recycle to demand, water source it can be integrated with other demand in other network. The unused water which is wastewater generation from sources will sent to the treatment before discharge to the environment.

2.3.2 Indirect Integration

In the indirect integration scheme, water networks are interconnected via a centralized utility hub that serves as a buffer as shown in Figure 2.5. The main advantage of using a centralized utility hub is that, it is more practical in handling a large number of water networks in the IPWI scheme. In particular, geographical distances between different water networks are much larger than typically encountered for within a single water network. Hence, an interplant network that includes a centralized utility hub will reduce the associated piping cost by pooling together water streams to be exported from each plant. A centralized utility hub is viable in the context of promoting sustainable development through industrial symbiosis between companies in close proximity. Conceptually, the utility hub can be seen as an internal water main in a single water network with the main objective to increase water network flexibility and controllability (Irene et al., 2008).

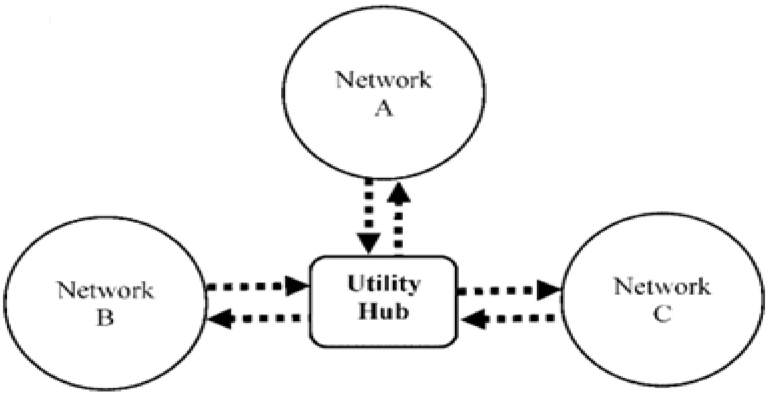

Figure 2.5: IPWI schemes (indirect integration)

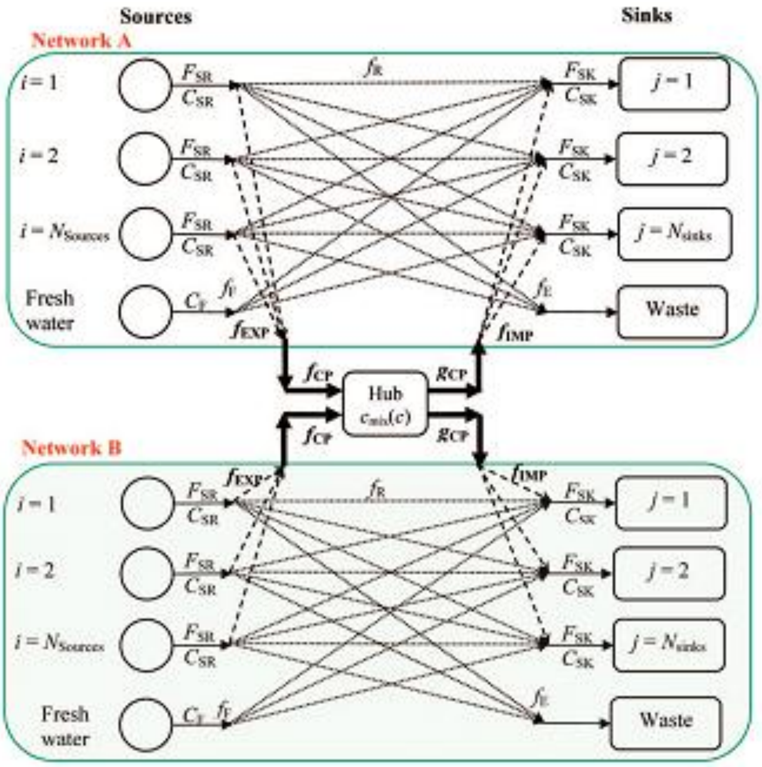

Figure 2.6: Superstructure for indirect integration

Figure 2.6 illustrate the superstructure for indirect integration process. The hub can acts as a storage tank that stores the water sources or demand for all network. Water that comes from source to hub is called as export water while water from hub to demand is called import water. The resulting of water mixture in the hub has a contaminant concentration.

2.3.2.1 Centralized Utility Hub with Wastewater Regeneration Unit

Recently, inter-plant is deal with the wastewater regeneration unit. In this scheme, the centralized utility hub consists a regeneration unit. The function of regeneration unit is to treat or improve water quality before use it again for further water recovery. The water in the centralized utility hub will be treated at a certain concentration level before export to the water network.

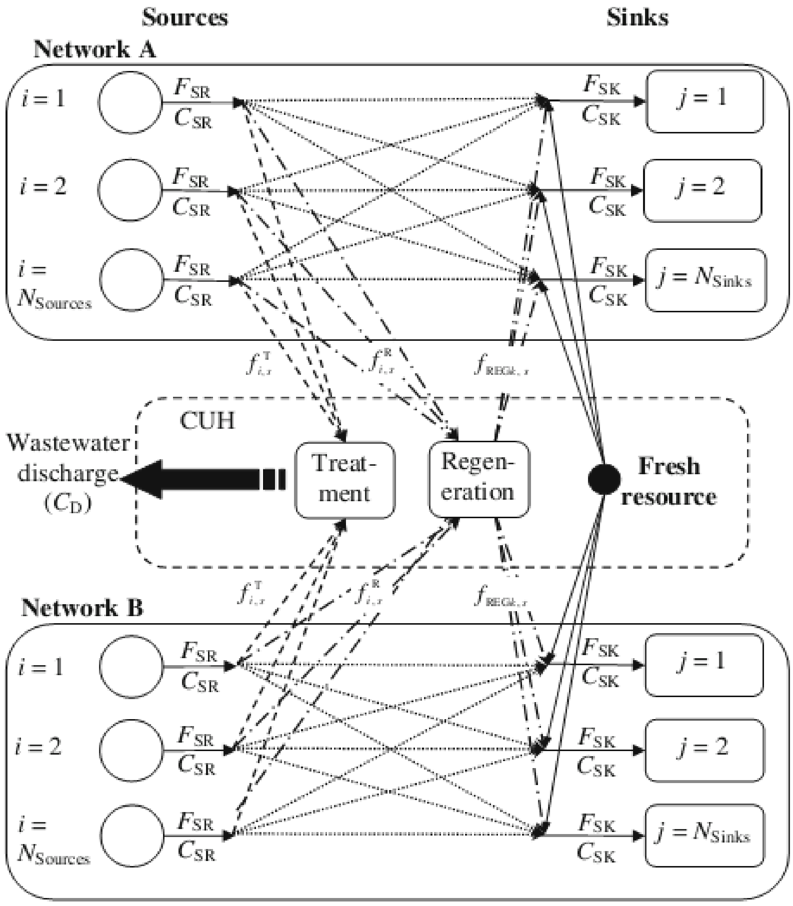

Figure 2.7: Superstructure for indirect integration via regeneration unit

2.4 WATER SYSTEM INTEGRATION

Typically, two approaches have been used to obtain good designs of these systems which are pinch analysis technology and mathematical programming.

2.4.1 Pinch Analysis Technology

In the past decades, research in water network synthesis based on insight-based pinch analysis techniques has evolved from the targeting of minimum fresh water and waste water to the targeting of minimum regeneration and wastewater treatment flow rates.

Wang and Smith (1994) proposed the first pinch-based method to maximize savings in a water network with reuse, recycling and regeneration strategies. The concept of limiting composite curves that was originally developed for utility targeting in water reuse/recycling network was extended to include targeting for network with regeneration–reuse and regeneration–recycling schemes. The minimum utility targets are located prior to detailed network design. This method is applicable for MTB water systems that involve single contaminant. The author extended their targeting and network design procedure for multiple contaminants but some of the graphical procedures for targeting and design are rather tedious since they require elaborate shifting of streams in the concentration versus mass load diagram.

Later on, Kuo and Smith (1998) pointed out that this approach may fail to obtain the true utility targets when the pinch points are relocated after regeneration. They proposed a new methodology where the minimum water targets are refined by migrating streams that have been classified into different water groups which include streams that are fed by freshwater and those that require regenerated water. The numbers of regeneration and effluent treatment units' targets were also included in their approach.

Hallale (2002) established an alternative graphical targeting method called the water surplus diagram that is applicable to NMTB. The authors located the minimum utility targets for a grassroots water network with reuse/recycle scheme and provide

---- RBALANCE =E= overall centralized main inlet and outlet flowrate balance

RBALANCE(A).. fcpA(A) + fcpB(B) - gcpA(A) - gcpB(B) =E= 0 ; (LHS = 0)

RBALANCE(B).. fcpA(A) + fcpB(B) - gcpA(A) - gcpB(B) =E= 0 ; (LHS = 0)

---- LBOUNDEXPORTA =L= lower boundry for export cross plant pipelines for netw
ork A

LBOUNDEXPORTA(A).. - fcpA(A) =L= 0 ; (LHS = 0)

LBOUNDEXPORTA(B).. - fcpA(A) =L= 0 ; (LHS = 0)

---- UBOUNDEXPORTA =G= upper boundary for export cross plant pipelines for net
work A

UBOUNDEXPORTA(A).. - fcpA(A) + 350*xind(A) =G= 0 ; (LHS = 0)

UBOUNDEXPORTA(B).. - fcpA(A) + 350*xind(A) =G= 0 ; (LHS = 0)

---- LBOUNDEXPORTB =L= lower boundry for export cross plant pipelines for netw
ork B

LBOUNDEXPORTB(A).. - fcpB(B) =L= 0 ; (LHS = 0)

LBOUNDEXPORTB(B).. - fcpB(B) =L= 0 ; (LHS = 0)

---- UBOUNDEXPORTB =G= upper boundary for export cross plant pipelines for net
work B

UBOUNDEXPORTB(A).. - fcpB(B) + 350*xind(B) =G= 0 ; (LHS = 0)